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CUMULATIVE FATIGUE DAMAGE AT ELEVATED TEMPERATURE

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SUMMARY

A study of cumulative fatigue damage at elevated temperatures was conducted using heat-treated SAE 4130 alloy steel. The S-N curves at room temperature, 400° F, and 800° F were obtained from rotating-beam fatigue tests. Two-step, three-step, and five-step cumulative-damage fatigue tests were conducted on rotating-beam fatigue specimens at room temperature, 400° F, and 800° F. The results of the cumulative-damage tests are compared with those of a theoretical analysis.

INTRODUCTION

The behavior of a material subjected to repeated applications of load is of importance in the structural design of aircraft. Consequently, investigators have compiled volumes of data on the fatigue properties of aircraft materials and the effect of numerous variables on these properties. Most of these data were obtained by repeatedly applying a constant amplitude of alternating stress to a specimen until failure occurred. By testing a number of specimens at different stress levels, an S-N curve is obtained in which stress is plotted against cycles to failure.

The data obtained from conventional fatigue tests at constant stress amplitudes are of questionable value for design applications in which the maximum intensity of stress is not constant during the life of the structure. This problem is of particular interest in aircraft design since the stresses produced by air loads, gust loads, engine vibrations, and landings vary in magnitude and duration. The problem is further complicated by the fact that repeated stressing of a material at one stress amplitude may have pronounced effects on the fatigue properties at other stress amplitudes.

A number of investigations have been conducted (refs. 1 to 17) to determine the effect of stressing a material at one stress amplitude on the fatigue life at a second stress amplitude. The evidence indicates that for both ferrous and aluminum alloys understressing, overstressing, and coaxing may produce considerable change in the fatigue properties of a material. There have been attempts to explain these effects as the result of cold-working, strain-aging, residual stresses, and specimen selectivity. None of these explanations appear to be adequate since they fail to account completely for all the experimental evidence.

Additional investigations have been conducted (refs. 18 to 22) in which the stress amplitude was varied according to some definite, usually periodic, program during the test. The results of tests of this type are difficult to interpret for design purposes unless the test load was varied in the same manner as that in which the load will vary in the part being designed. Since there are an infinite number of possible service stress histories, the accumulation of data in this manner would appear to be an endless task.

In order to obtain a rational design procedure it is necessary first to establish a hypothesis of fatigue damage. It appears reasonable to assume that a material subjected to repeated stressing undergoes some damage during each cycle of stress and that this damage accumulates to the point of failure. With such a hypothesis it is possible to relate the behavior of a material subjected to cycles of varying stress amplitude to its behavior when subjected to cycles of constant stress amplitude. It is then possible to design a member that will be subjected to varying stress amplitudes during its life by use of the conventional S-N curve and the loading spectrum for the member (refs. 20 and 23 to 25).

This investigation was carried out at the University of Alabama under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

D	fatigue damage
E	endurance limit
k	constant
N	number of loading cycles to failure at stress S
n	number of loading cycles applied at stress S
R	cycle ratio, $\frac{n}{N}$
S	stress

W net work absorbed at failure or work done to failure

$\gamma = \frac{S - E}{E}$

Subscripts:

1, 2, . . . n indicates steps or levels

CUMULATIVE-DAMAGE STUDIES

Miner (ref. 26) proposed the first usable hypothesis of fatigue damage by relating damage at each stress amplitude to the net work that may be absorbed by a material. Miner assumed that fatigue damage could be expressed as the ratio of the number of loading cycles applied at a given stress to the number of cycles required to produce failure at the given stress. This ratio is referred to as the cycle ratio. Miner further assumed that if a material was subjected to repeated loading at more than one stress amplitude failure would occur when the sum of the cycle ratios became unity. This simple concept of cumulative damage may be expressed symbolically as follows: If

W net work absorbed at failure or work done to failure

W_1 work absorbed at stress S_1 in n_1 cycles

n_1 number of loading cycles applied at stress S_1

N_1 number of loading cycles to failure at stress S_1

R_1 cycle ratio at stress S_1

then, the first assumption may be expressed as

$$\frac{W_1}{W} = \frac{n_1}{N_1} = R_1$$

and the second assumption may be expressed as

$$W_1 + W_2 + W_3 + \ . \ . \ . \ W_n = W$$

or

$$\frac{W_1}{W} + \frac{W_2}{W} + \frac{W_3}{W} + \ldots \frac{W_n}{W} = 1$$

from which

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \ldots \frac{n_n}{N_n} = 1$$

or

$$R_1 + R_2 + R_3 + \ldots R_n = 1$$

The last equation which may be expressed as $\sum \frac{n}{N} = 1$ is frequently referred to as Miner's sum or the cumulative cycle ratio.

To verify this hypothesis, Miner performed a series of 22 axial-load fatigue tests on sheet specimens and riveted specimens of 2024-T3 alclad aluminum. Individual specimens were each subjected to two, three, or four different stress amplitudes. The average value of the cumulative cycle ratio was 1.015 with a minimum of 0.61 and a maximum of 1.45. Although the average value of the cumulative cycle ratio is very nearly unity as predicted by Miner's theory, the experimental evidence is not conclusive because of the relatively small number of tests and the scatter of the data.

Further investigations have shown that there are a number of additional factors not considered by Miner that influence fatigue damage. For example, it has been shown that regardless of whether a high or low stress is applied first, the number of different stress amplitudes applied and the magnitude of each stress level relative to the endurance limit are among the variables affecting fatigue damage.

Brueggeman, Mayer, and Smith (ref. 27) conducted a series of axial-load tests on 93 specimens of 2024-T3 aluminum-alloy sheet containing a drilled hole. All specimens were subjected to two-step tests in which a given number of cycles were applied at one stress followed by stressing at a second stress until failure. When the initial stress was less than the second stress, the cumulative cycle ratio at failure exceeded unity. When the initial stress was greater than the second stress, the cumulative cycle ratio was less than unity.

Bennett (ref. 10) performed a series of tests on SAE 4130 steel using both axial load and rotating bending machines. His results with respect to the effect of the sequence in which the stresses are applied are identical to those of Brueggeman, Mayer, and Smith.

Richart and Newmark (ref. 28) have proposed a hypothesis in which the effect of the sequence in which the stresses are applied is considered. If fatigue damage is denoted by the term D, curves of cycle ratio against damage may be plotted. It is assumed that the damage is zero before applying any stresses and unity when a specimen has failed because of repeated stressing. Points on the conventional S-N curve represent a cycle ratio of unity and a damage of unity. As a material is subjected to repeated stressing the cycle ratio increases and the damage increases. However, the exact relationship between cycle ratio and damage is not known.

Miner assumed a linear relationship between cycle ratio and damage as shown by the line $D = R$ in figure 1. Richart and Newmark assume that the relation between cycle ratio and damage is a function of the stress as shown by the curves S_1, S_2, and S_3 in figure 1 in which $S_1 > S_2 > S_3$. The assumption of Richart and Newmark agrees with the experimental evidence which indicates that at low stress levels a relatively small amount of damage occurs during the early cycles but increases rapidly toward the end of the endurance lift. On the other hand, at high stress levels a greater amount of damage occurs during the early cycles than during the latter stages. This assumption agrees with the conclusions of other investigators that the cumulative cycle ratio at failure is greater than unity when the initial stress is less than the final stress and less than unity when the initial stress is larger than the final stress.

In order to apply the hypothesis of Richart and Newmark it is necessary to determine experimentally curves of damage plotted against cycle ratio for various stresses in addition to the conventional S-N curve. Since curves of damage plotted against cycle ratio are not readily available for most materials, it would be difficult to use this procedure in design.

Grover, Bishop, and Jackson (ref. 29) conducted a number of two-step cumulative-damage axial-load fatigue tests on sheet specimens of 2024-T3 aluminum alloy, 7075-T6 aluminum alloy, and SAE 4130 steel. For the tests in which the low stress was applied first, the cumulative cycle ratio at failure exceeded unity for all three materials. For the tests in which the high stress was applied first, the cumulative cycle ratio at failure was less than unity for the SAE 4130 steel specimens. However, the tests on the aluminum-alloy specimens in which the high stress was applied first had a cumulative cycle ratio at failure greater than unity.

Marco and Starkey (ref. 30) reported a number of rotating-beam fatigue tests of 76S-T61 aluminum alloy and SAE 4340 steel in which cumulative damage was studied. The results of these tests also show the effect of the order in which the stresses are applied. During the course of each test the stress was changed 2, 4, 6, 10, 15, or 20 times. There was no well-defined effect due to the number of different stresses applied.

A very extensive axial-load cumulative-fatigue-damage study of alclad 7075-T6 and alclad 2024-T3 aluminum-alloy sheet was conducted by Smith, Howard, and Smith (ref. 31). A total of 805 specimens were tested under various loading conditions with all the cumulative-damage tests being two-step tests. Seventy-two percent of the average cumulative cycle ratios were within 20 percent of unity and 40 percent were within 10 percent of unity. The smallest average cumulative cycle ratio of a group of four similar specimens was 0.568 and the largest, 1.440. There was no systematic variation of the cumulative cycle ratio with the stress amplitude, the sheet thickness, the mean stress, or the alloy used.

Schijue and Jacobs (refs. 32) reported a number of cumulative-damage axial-load fatigue tests on both notched and unnotched specimens of 2024-T3 alclad. Considerable scatter in the results makes interpretation difficult. For example, in one series of 10 identical tests on notched specimens in which the high stress was applied first, the cumulative cycle ratio at failure varied from 0.19 to more than 18.

Low (ref. 33) conducted a number of reversed-bending cumulative-damage tests on aluminum-alloy sheet. Instead of the conventional S-N curve, a curve of maximum fiber strain plotted against number of cycles to failure was obtained which was similar in shape to the conventional S-N curve for nonferrous materials. In the cumulative-damage tests, the value of the cumulative cycle ratio at failure varied from 0.75 to 1.49. A plot of the maximum fiber strain against the number of cycles to failure at the final strain is linear which suggests another variable that may influence the value of the cumulative cycle ratio.

Henry (ref. 34) has made a theoretical analysis of fatigue-damage accumulation based on the assumption that the S-N curve may be represented by the equation $N = \frac{k}{S - E}$ where k is a constant and E is the endurance limit. An expression denoted by γ is called the overstress ratio and defined as

$$\gamma = \frac{S - E}{E}$$

Henry assumes that as a material accumulates fatigue damage the values of k and E change so that after a material has accumulated a certain amount of fatigue damage it has an S-N curve different from the S-N curve of the virgin material. Using these assumptions, Henry has derived the following expression for the fatigue damage D (where R is cycle ratio):

$$D = \frac{R}{1 + \frac{1 - R}{\gamma}}$$

Using this expression Henry has analyzed the experimental data of Bennett (ref. 10) and Kommers (refs. 9). There is close agreement between the experimental results and the results predicted by Henry's theory. Henry's theory may be applied to predict the cumulative cycle ratio when only the conventional S-N curves of a material are available.

All the fatigue-damage tests reported in the literature were conducted at room temperature. The present investigation was undertaken to determine the fatigue-damage characteristics of a typical aircraft steel at elevated temperatures.

MATERIAL

The material used in this investigation was supplied as 225 feet of $\frac{1}{2}$-inch-diameter round rod from one heat of SAE 4130 steel which was heat-treated to military specification S 6758, condition F5.

The chemical analysis was as follows:

Carbon, percent by weight	0.33
Manganese, percent by weight	0.46
Phosphorus, percent by weight	0.014
Sulphur, percent by weight	0.010
Silicon, percent by weight	0.30
Nickel, percent by weight	0.17
Chromium, percent by weight	0.90
Molybdenum, percent by weight	0.20

The room-temperature mechanical properties were determined using American Society for Metals standard 5/16-inch tension specimens. These tests were performed in a Baldwin 60,000-pound universal testing machine with Huggenberger Tensometers used to measure strains. The average room-temperature mechanical properties from six tests were as follows:

Ultimate strength, psi	133,800
Proportional limit, psi	80,000
Yield strength (0.2-percent offset), psi	111,300
Young's modulus, psi	30,040,000
Elongation in 1 inch, percent	26
Reduction of area, percent	65.7
Rockwell hardness	C26.3

The average tensile stress-strain curve is shown in figure 2.

APPARATUS AND PROCEDURE

For comparison purposes, a series of cumulative fatigue tests were conducted at room temperature using a Krouse rotating bending fatigue machine operating at 4,800 rpm.

The elevated-temperature tests were conducted in a Krouse high-speed, high-temperature, repeated-stress machine at a testing speed of 4,800 rpm. This machine is described in detail in reference 35.

The dimensions of the specimens used for all the fatigue tests are given in figure 3. The specimens were machined from the $\frac{1}{2}$- inch-diameter rod and then polished. The machining marks were removed with 120-grit Metalite cloth and 280-grit Metalite cloth was used for the final polish. All circumferential scratches were removed by polishing parallel to the longitudinal axis of the specimen while it was slowly rotated in a lathe. Approximately 0.002 inch of the material was removed in the polishing operation.

For the elevated-temperature tests the specimens were inserted in the furnace at room temperature and rotated at zero stress while the furnace temperature was increased to the test temperature. The testing temperature was obtained in approximately 45 minutes. After reaching the test temperature an additional 15 minutes was allowed to obtain temperature equilibrium before applying the load.

To obtain the S-N curve at each temperature, a series of conventional fatigue tests were performed. A minimum of four specimens were tested at each of 10 different stress levels.

The cumulative-damage tests at each temperature were conducted in three parts: A series of two-step tests, a series of three-step tests, and a series of five-step tests.

The two-step tests were conducted according to the following schedule:

(1) Initial stress S_1 less than final stress S_2
 (a) Cycle ratio of 0.25 at S_1 to failure at S_2
 (b) Cycle ratio of 0.50 at S_1 to failure at S_2
 (c) Cycle ratio of 0.75 at S_1 to failure at S_2

(2) Initial stress S_1 greater than final stress S_2
 (a) Cycle ratio of 0.25 at S_1 to failure at S_2
 (b) Cycle ratio of 0.50 at S_1 to failure at S_2
 (c) Cycle ratio of 0.75 at S_1 to failure at S_2

A minimum of four specimens were tested in each stress sequence. The entire schedule was then repeated for a different set of stresses S_1 and S_2.

The three-step tests were conducted according to the following schedule:

(1) Stress level progressively increasing, $S_1 < S_2 < S_3$:
 Cycle ratio of 0.30 at S_1 followed by cycle ratio of 0.30 at S_2 to failure at S_3

(2) Stress level progressively decreasing, $S_1 > S_2 > S_3$:
 Cycle ratio of 0.30 at S_1 followed by cycle ratio of 0.30 at S_2 to failure at S_3

A minimum of four specimens were tested in each sequence.

The five-step tests were conducted according to the following schedule:

(1) Stress level progressively increasing, $S_1 < S_2 < S_3 < S_4 < S_5$
(2) Stress level progressively decreasing, $S_1 > S_2 > S_3 > S_4 > S_5$
(3) Stress level alternating, $S_1 < S_2$, $S_2 > S_3$, $S_3 < S_4$, $S_4 > S_5$

A cycle ratio of 0.20 was applied at each of the first four stress levels followed by stressing until failure at the final stress level. A minimum of four specimens were tested in each sequence.

RESULTS AND DISCUSSION

Room Temperature

The data used to obtain the S-N curve at room temperature are summarized in table I. The mean S-N curve shown in figure 4 was obtained by the method of reference 36, as illustrated in appendix A. The reasonable range (ref. 36) of the mean S-N curve is ±300 psi. For a single specimen, the average value of cycle ratio $\frac{n}{N}$ was 1.035 with a minimum value of 0.780 and a maximum value of 1.343. Seventy-five percent of the specimens had a value of $\frac{n}{N}$ within 15 percent of unity and 61 percent of the specimens had a value of $\frac{n}{N}$ within 10 percent of unity.

The results of the two-step tests at room temperature are summarized in table II. For 24 specimens to which the low stress was applied first, the average value of the cumulative cycle ratio at failure was 1.169. For 24 specimens to which the high stress was applied first, the average value of the cumulative cycle ratio was 0.809.

The results of the three-step tests at room temperature are given in table III. For the specimens for which the stress level was progressively increased during the test, the average value of the cumulative cycle ratio was 1.644. For the specimens for which the stress level was progressively decreased during the test, the average value of the cumulative cycle ratio was 0.787.

The results of the five-step tests at room temperature are summarized in table IV. When the stress level was progressively increased the average value of the cumulative cycle ratio was 1.107. When the stress level was progressively decreased the average value of the cumulative cycle ratio was 0.875. For specimens for which the stress level was alternately increased and decreased, the average cumulative cycle ratio was 0.846.

As other investigations have shown, the data given in tables II, III, and IV indicate that at room temperature the order in which the stresses are applied affects the cumulative cycle ratio. In general, when a low stress is applied first, the damage at the low stress is less than that predicted by Miner and when a high stress is applied first the damage is greater than that predicted.

Henry (ref. 34) considered the effect of the order in which the stresses are applied in developing his theory. For each of the cumulative-damage tests, the theoretical cumulative cycle ratio has been computed using Henry's theory and compared with the experimental results in table V. A sample computation using Henry's theory is given in appendix B. In general, the test results at room temperature show close agreement with the values predicted by Henry.

Temperature, 400° F

The test results used to obtain the mean S-N curve at 400° F are presented in tabular form in table VI and shown graphically in figure 5. The reasonable range of the mean curve is ±730 psi. For a single specimen, the average value of $\frac{n}{N}$ was 1.016 with a minimum value of 0.465 and a maximum value of 1.595. Fifty-one percent of the specimens had a value of $\frac{n}{N}$ within 15 percent of unity and 41 percent of the specimens had a value of $\frac{n}{N}$ within 10 percent of unity. The scatter is somewhat larger than that found in the room-temperature tests. This greater scatter may be attributed to the introduction of the temperature variable.

The results of the two-step tests at 400° F are presented in tables VII and VIII. In table VII the cycle ratio was computed using the mean S-N curve whereas in table VIII the computations were based on the minimum S-N curve. The computations based on the minimum S-N curve are presented to show that, in the cumulative-damage tests, the range of values obtained for the cumulative cycle ratio cannot be explained solely on the basis of scatter. Table VIII shows that the cumulative cycle ratio is less than unity when the high stress is applied first even when the computations are based on the minimum fatigue life. Table VIII also shows that if the computations are based on the minimum S-N curve the effect of the order in which the stresses are applied is the same at elevated temperature as it is at room temperature. For specimens to which the low stress was applied first the average value of the cumulative cycle ratio was 1.283. For specimens to which the high stress was applied first the average value of the cumulative cycle ratio was 0.848.

Tables IX and X present the results of three-step tests at 400° F. Based on the minimum S-N curve, the average value of the cumulative cycle ratio was 1.862 for specimens subjected to progressively increasing stresses and 0.865 for specimens subjected to progressively decreasing stresses.

The results of the five-step tests at 400° F are given in tables XI and XII. Based on the minimum curve, the average value of the cumulative cycle ratio was 2.456 for specimens subjected to progressively increasing stresses and 1.128 for specimens on which the stress level was alternately increased and decreased.

In table XIII the experimental results are compared with the results predicted by Henry's theory. All the computations in this table are based on the minimum fatigue life. Although the agreement is not so close as that at room temperature, Henry's theory appears to predict satisfactorily the effect of stress sequence on the cumulative cycle ratio.

Temperature, 800° F

The test results used to obtain the mean S-N curve at 800° F are presented in tabular form in table XIV and shown graphically in figure 6. The reasonable range of the mean curve is ±410 psi. For a single specimen, the average value of $\frac{n}{N}$ was 1.161 with a minimum value of 0.345 and a maximum value of 2.567. Although this represents greater scatter than the room-temperature tests or the tests at 400° F, the reasonable range of the mean curve is less because of the larger number of specimens tested. Only 20 percent had a value of $\frac{n}{N}$ within 20 percent of unity and 15 percent of the specimens had a value of $\frac{n}{N}$ within 10 percent of unity.

The results of the two-step tests at 800° F are presented in table XV. For 27 specimens to which the low stress was applied first, the average value of the cumulative cycle ratio at failure was 1.302. For 26 specimens to which the high stress was applied first, the average value of the cumulative cycle ratio at failure was 0.594. The effect of the order in which the stresses were applied is the same as that noted at room temperature and at 400° F.

Table XVI presents the results of the three-step tests at 800° F. For the specimens on which the stress level was progressively increased during the test, the average value of the cumulative cycle ratio at failure was 0.584. For specimens on which the stress level was progressively decreased during the test, the average value of the cumulative cycle ratio at failure was 0.450. These data again indicate the effect of the order of application of stress on the cumulative cycle ratio at failure. However, in the progressively increasing stress tests, the cumulative cycle ratio was not greater than unity.

In table XVII, the results of the five-step tests at 800° F are given. The average value of the cumulative cycle ratio at failure was 0.884 for specimens subjected to progressively increasing stresses, 0.459 for specimens subjected to progressively decreasing stresses, and 0.379 for specimens on which the stress level was alternately increased and decreased. As in the three-step tests, the cumulative cycle ratio at failure was less than unity regardless of the order in which the stresses were applied.

The comparison of the experimental results at 800° F with those obtained by Henry's theory is given in table XVIII. Although Henry's theory appears to predict the proper trend, the agreement is not close in the progressively increasing three-step and five-step tests.

CONCLUDING REMARKS

A study of cumulative fatigue damage at elevated temperatures using heat-treated SAE 4130 alloy steel has been made. In using fatigue data, it is important to recognize that the fatigue curve represents only average values. An individual specimen may exhibit a fatigue life considerably different from the average. The data obtained indicate that fatigue testing at elevated temperatures may be expected to result in even greater scatter than that which appears at room temperature. When this already large scatter is coupled with further inaccuracies introduced by testing at more than one stress level, the scatter may become large enough to overshadow the effects of the variables being studied. However, the results indicate that the frequently accepted assumption that damage is proportional to cycle ratio errs on the unsafe side under certain conditions. These results cannot be explained solely on the basis of scatter.

Since Henry (Transactions of A.S.M.E., August 1955) assumed an equation for the S-N curve that does not fit the elevated-temperature data, closer agreement may be obtained by the use of a different equation in the analysis.

The analysis developed by Henry satisfactorily predicts the cumulative cycle ratio at failure in room-temperature tests. At elevated temperatures, further study is indicated to arrive at a satisfactory analysis.

University of Alabama,
University, Ala., March 25, 1957.

APPENDIX A

METHOD FOR OBTAINING MEAN S-N CURVE

In order to obtain the mean life at each stress amplitude, the mean S-N curve was determined by the method proposed in reference 36. This method assumes that fatigue data follow a normal distribution on the stress scale which has been shown to be reasonably correct (ref. 37). The mean S-N curve is established by a statistical technique through trial and error. To illustrate this method, a portion of the room-temperature data has been replotted in figure 7.

Groups of points are selected so that each group contains at least 5 test points within a 10 to 1 life scatter. The data plotted in figure 7 have been divided into two groups denoted A and B. After selecting the groups, the center of each group is determined by inspection and the vertical lines TT' drawn through the center. The center of each group represents the approximate mean-log-life of the group.

The mean stress of each group at the mean life is then determined. For each plotted point, the vertical displacement from the estimated curve is measured and expressed in terms of stress. In figure 7, the vertical displacement of one of the points in group A is shown as $\Delta S = 1{,}500$ psi. This displacement is considered positive when the point lies above the curve. The algebraic sum and the mean of these vertical displacements are then computed for each group. For group A, the algebraic sum is given by

$$\sum(\Delta S) = 700 + 500 - 500 - 1{,}100 + 1{,}500 + 1{,}100 + 0 - 450 = 1{,}750 \text{ psi}$$

and the mean stress is $\dfrac{1{,}750}{8} = 219$ psi.

The mean is then measured off on line TT' from points z to w. Point w lies above the curve when the mean is positive and below the curve when the mean is negative. The mean of each group is computed and a new curve, shown in figure 7 as the corrected curve, is drawn through the points labeled w in each group.

In reference 36 it is recommended that the entire procedure be repeated until the stresses of any curve are within 2 percent of the stress of the preceding curve. The final curve obtained is the mean curve. The reasonable range is defined as

$$\pm \frac{2C}{\sqrt{N}} \sigma$$

where

N number of specimens

$$C = \sqrt{\frac{N}{2}} \times \frac{\left(\frac{N - 3}{2}\right)!}{\left(\frac{N - 2}{2}\right)!}$$

σ uncorrected standard deviation, $\sqrt{\sum_{i=1}^{N} \frac{\left(X_i - \bar{X}\right)^2}{N}}$

$X_i - \bar{X}$ vertical displacement of any point from corrected mean curve

For the room-temperature data, the standard deviation of the 41 specimens was 945 psi and the reasonable range ±302 psi. This indicates that the probable position of the real mean curve is within ±302 psi of the position shown in figure 4.

APPENDIX B

EXAMPLE OF COMPUTATION OF CUMULATIVE CYCLE RATIO

To illustrate the method of analysis proposed by Henry, the computation of the theoretical cumulative cycle ratio is carried out in detail for one specimen at room temperature.

Assume that a specimen is to be subjected to a cycle ratio R_1 of 0.250 at a stress S_1 of 80,000 psi followed by stressing at S_2 of 88,000 psi until failure. From figure 4 the endurance limit E at room temperature is 77,000 psi. The overstress ratio at S_1 is given by

$$\gamma_1 = \frac{S_1 - E}{E} = \frac{80,000 - 77,000}{77,000} = 0.039$$

The overstress ratio at S_2 is

$$\gamma_2 = \frac{S_2 - E}{E} = \frac{88,000 - 77,000}{77,000} = 0.143$$

The damage due to imposing a cycle ratio of 0.250 at S_1 is

$$D_1 = \frac{R_1}{1 + \frac{1 - R_1}{\gamma_1}} = \frac{0.250}{1 + \frac{0.750}{0.039}} = 0.012$$

The damage due to stressing at S_1 represents a cycle ratio at S_2 equal to

$$R_2 = \frac{D_1\left(1 + \gamma_2\right)}{D_1 + \gamma_2} = \frac{0.012(1.143)}{0.012 + 0.143} = 0.090$$

The life remaining at S_2 is $\left(1 - R_2\right)$ or 0.910. The cumulative cycle ratio is the result of a cycle ratio of 0.250 at S_1 plus a cycle ratio of 0.910 at S_2. Therefore,

$$\sum \frac{n}{N} = 0.250 + 0.910 = 1.160$$

As shown in table II, the average experimental value obtained for this condition was 1.134.

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TABLE I.- RESULTS OF ROOM-TEMPERATURE TESTS AT ONE STRESS LEVEL

[N obtained from mean S-N curve]

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F75	98,000	28,700	33,500	0.857	10.4
12F76	98,000	30,700	33,500	.916	4.3
12F80	98,000	34,200	33,500	1.021	6.7
12F74	98,000	34,600	33,500	1.033	7.9
				Av. .957	Av. ±7.3
12F63	94,000	50,000	53,500	.935	12.2
12F67	94,000	53,300	53,500	.996	6.5
12F64	94,000	60,300	53,500	1.127	5.8
12F65	94,000	64,300	53,500	1.202	12.9
				Av. 1.065	Av. ±9.4
12F61	90,000	67,100	86,000	.780	9.3
12F62	90,000	73,400	86,000	.853	.8
12F59	90,000	75,000	86,000	.872	1.4
12F60	90,000	80,200	86,000	.933	8.4
				Av. .860	Av. ±5.0
12F72	88,000	105,300	110,000	.957	14.1
12F79	88,000	110,200	110,000	1.002	10.1
12F71	88,000	132,200	110,000	1.202	7.8
12F78	88,000	142,200	110,000	1.293	16.5
				Av. 1.114	Av. ±12.1
12F2	85,000	138,000	158,000	.873	17.6
12F4	85,000	164,500	158,000	1.041	1.7
12F5	85,000	173,000	158,000	1.095	3.3
12F3	85,000	193,600	158,000	1.225	15.7
				Av. 1.059	Av. ±9.6
12F9	84,000	170,100	173,000	983	3.6
12F11	84,000	173,800	173,000	1.005	1.5
12F6	84,000	175,800	173,000	1.016	.4
12F10	84,000	186,200	173,000	1.076	5.5
				Av. 1.020	Av. ±2.8

TABLE I.- RESULTS OF ROOM-TEMPERATURE TESTS AT

ONE STRESS LEVEL - Concluded

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F12	82,000	225,000	224,000	1.004	6.3
12F13	82,000	244,000	224,000	1.091	1.9
12F15	82,000	244,800	224,000	1.093	2.1
12F14	82,000	245,500	224,000	1.096	2.3
				Av. 1.071	Av. ±3.2
12F17	80,000	228,000	282,000	.809	18.1
12F19	80,000	270,500	282,000	.959	3.0
12F18	80,000	276,400	282,000	.980	.8
12F16	80,000	339,200	282,000	1.203	21.8
				Av. .988	Av. ±10.9
12F23	78,000	396,300	410,000	.967	18.3
12F25	78,000	444,300	410,000	1.084	8.5
12F21	78,000	549,600	410,000	1.340	13.2
12F22	78,000	550,600	410,000	1.343	13.4
				Av. 1.184	Av. ±13.4
12F28	77,000	495,900	(a)		
12F30	77,000	537,100	(a)		
12F29	77,000	1,001,000	(a)		
12F81	77,000	11,793,700	(a b)		
12F27	77,000	12,404,800	(a b)		

[a]Stress corresponds to endurance limit.
[b]Specimen did not fail.

TABLE II.- RESULTS OF TWO-STEP TESTS AT ROOM TEMPERATURE

[From mean curve: N at 80,000 psi is 282,000 cycles, N at 82,000 psi is 224,000 cycles, N at 88,000 psi is 110,000 cycles, and N at 94,000 psi is 53,500 cycles]

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F90	80,000	88,000	0.250	0.935	1.185	4.5
12F119	80,000	88,000	.250	.833	1.083	5.5
12F120	80,000	88,000	.250	.749	.999	12.0
12F122	80,000	88,000	.250	1.018	1.268	11.8
					Av. 1.134	Av. ±8.5
12F123	80,000	88,000	.500	.934	1.434	3.2
12F124	80,000	88,000	.500	.935	1.435	3.1
12F125	80,000	88,000	.500	.997	1.497	1.1
12F131	80,000	88,000	.500	1.061	1.561	5.4
					Av. 1.481	Av. ±3.2
12F127	80,000	88,000	.750	.794	1.544	12.4
12F128	80,000	88,000	.750	.792	1.542	12.2
12F132	80,000	88,000	.750	.364	1.114	18.9
12F133	80,000	88,000	.750	.547	1.297	5.6
					Av. 1.374	Av. ±12.3
12F134	88,000	80,000	.250	.545	.795	7.4
12F135	88,000	80,000	.250	.567	.817	10.4
12F136	88,000	80,000	.250	.369	.619	16.4
12F138	88,000	80,000	.250	.488	.738	.3
					Av. .740	Av. ±8.6
12F139	88,000	80,000	.500	.136	.631	23.9
12F140	88,000	80,000	.500	.347	.847	2.2
12F174	88,000	80,000	.500	.382	.882	6.4
12F175	88,000	80,000	.500	.457	.957	15.4
					Av. .829	Av. ±12.0
12F143	88,000	80,000	.750	.325	1.075	2.9
12F144	88,000	80,000	.750	.713	1.463	32.2
12F145	88,000	80,000	.750	.266	1.016	8.2
12F146	88,000	80,000	.750	.123	.873	21.1
					Av. 1.107	Av. ±16.1

TABLE II.- RESULTS OF TWO-STEP TESTS AT ROOM TEMPERATURE - Concluded

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F178	82,000	94,000	0.250	0.587	0.837	11.0
12F179	82,000	94,000	.250	.630	.880	6.4
12F180	82,000	94,000	.250	.594	.844	10.2
12F181	82,000	94,000	.250	.948	1.198	27.4
					Av. .940	Av. ±13.8
12F182	82,000	94,000	.500	.540	1.040	3.4
12F183	82,000	94,000	.500	.867	1.267	25.9
12F184	82,000	94,000	.500	.424	.924	6.2
12F185	82,000	94,000	.500	.292	.792	21.3
					Av. 1.006	Av. ±14.2
12F187	82,000	94,000	.750	.426	1.176	8.9
12F188	82,000	94,000	.750	.368	1.118	3.5
12F189	82,000	94,000	.750	.204	.954	11.8
12F230	82,000	94,000	.750	.320	1.070	.9
					Av. 1.080	Av. ±6.3
12F190	94,000	82,000	.250	.254	.504	22.7
12F191	94,000	82,000	.250	.291	.541	17.0
12F192	94,000	82,000	.250	.633	.883	35.4
12F193	94,000	82,000	.250	.431	.681	4.4
					Av. .652	Av. ±19.9
12F194	94,000	82,000	.500	.039	.539	17.7
12F195	94,000	82,000	.500	.138	.638	2.6
12F196	94,000	82,000	.500	.252	.752	14.8
12F197	94,000	82,000	.500	.192	.692	5.6
					Av. .655	Av. ±10.2
12F198	94,000	82,000	.750	.162	.912	4.8
12F199	94,000	82,000	.750	.034	.784	10.0
12F201	94,000	82,000	.750	.010	.760	12.6
12F231	94,000	82,000	.750	.275	1.025	17.8
					Av. .870	Av. ±11.3

TABLE III.- RESULTS OF THREE-STEP TESTS AT ROOM TEMPERATURE

[From mean curve: N at 82,000 psi is 224,000 cycles, N at 88,000 psi is 110,000 cycles, and N at 94,000 psi is 53,500 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	Cumulative cycle ratio, $\sum\frac{n}{N}$	Deviation from average, percent
12F232	82,000	88,000	94,000	0.300	0.300	1.125	1.725	4.9
12F233	82,000	88,000	94,000	.300	.300	1.052	1.652	.5
12F235	82,000	88,000	94,000	.300	.300	.746	1.346	18.1
12F236	82,000	88,000	94,000	.300	.300	1.254	1.854	12.8
							Av. 1.644	Av. ±9.1
12F237	94,000	88,000	82,000	.300	.300	.175	.775	1.5
12F238	94,000	88,000	82,000	.300	.300	.169	.769	2.3
12F240	94,000	88,000	82,000	.300	.300	.218	.818	3.9
12F241	94,000	88,000	82,000	.300	.300	.186	.786	.1
							Av. .787	Av. ±2.0

TABLE IV.- RESULTS OF FIVE-STEP TESTS AT ROOM TEMPERATURE

[From mean curve: N at 80,000 psi is 282,000 cycles, N at 82,000 psi is 224,000 cycles, N at 85,000 psi is 158,000 cycles, N at 88,000 psi is 110,000 cycles, N at 91,000 psi is 77,000 cycles, and N at 94,000 psi is 53,500 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	R_4, $\frac{n_4}{N_4}$	R_5, $\frac{n_5}{N_5}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F242	82,000	85,000	88,000	91,000	94,000	0.200	0.200	0.200	0.200	0.232	1.032	6.8
12F243	82,000	85,000	88,000	91,000	94,000	.200	.200	.200	.200	.553	1.353	22.2
12F244	82,000	85,000	88,000	91,000	94,000	.200	.200	.200	.200	.140	.940	15.1
12F245	82,000	85,000	88,000	91,000	94,000	.200	.200	.200	.200	.093	.893	19.3
12F246	82,000	85,000	88,000	91,000	94,000	.200	.200	.200	.200	.516	1.316	18.9
											Av. 1.107	Av. ±16.5
12F247	94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.200	.196	.996	13.8
12F248	94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.200	.107	.907	3.7
12F249	94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.200	.183	.983	12.3
12F250	94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.149	0	.749	14.4
12F251	94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.138	0	.738	15.7
											Av. .875	Av. ±12.0
12F252	80,000	88,000	80,000	88,000	80,000	.200	.200	.200	.200	.117	.917	8.4
12F254	80,000	88,000	80,000	88,000	80,000	.200	.200	.200	.128	0	.728	13.9
12F255	80,000	88,000	80,000	88,000	80,000	.200	.200	.200	.200	.113	.913	7.9
12F256	80,000	88,000	80,000	88,000	80,000	.200	.200	.200	.200	.025	.825	2.5
											Av. .846	Av. ±8.2

TABLE V.- COMPARISON OF ROOM-TEMPERATURE TEST RESULTS WITH RESULTS COMPUTED BY HENRY'S THEORY (REF. 34)

S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	$\frac{n_1}{N_1}$	$\frac{n_2}{N_2}$	$\frac{n_3}{N_3}$	$\frac{n_4}{N_4}$	Cumulative cycle ratio	
									Test average	Henry's theory
Two-step tests										
80,000	88,000				0.250				1.134	1.160
80,000	88,000				.500				1.481	1.271
80,000	88,000				.750				1.374	1.279
88,000	80,000				.250				.740	.718
88,000	80,000				.500				.829	.733
88,000	80,000				.750				1.107	.840
82,000	94,000				.250				.940	1.150
82,000	94,000				.500				1.006	1.246
82,000	94,000				.750				1.080	1.247
94,000	82,000				.250				.652	.750
94,000	82,000				.500				.655	.753
94,000	82,000				.750				.870	.851
Three-step tests										
82,000	88,000	94,000			0.300	0.300			1.644	1.218
94,000	88,000	82,000			.300	.300			.787	.785
Five-step tests										
82,000	85,000	88,000	91,000	94,000	0.200	0.200	0.200	0.200	1.107	1.207
94,000	91,000	88,000	85,000	82,000	.200	.200	.200	.200	.875	.841
80,000	88,000	80,000	88,000	80,000	.200	.200	.200	.200	.846	.928

TABLE VI.- RESULTS OF 400° F TESTS AT ONE STRESS LEVEL

[N obtained from mean S-N curve]

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F114	84,000	55,500	49,000	1.133	7.5
12F102	84,000	52,400	49,000	1.069	1.4
12F115	84,000	50,000	49,000	1.020	3.3
12F103	84,000	48,700	49,000	.994	5.7
				Av. 1.054	Av. ±4.5
12F98	80,000	82,500	80,000	1.031	10.6
12F99	80,000	77,200	80,000	.965	3.5
12F116	80,000	72,200	80,000	.903	3.1
12F100	80,000	66,400	80,000	.830	11.0
				Av. .932	Av. ±7.1
12F95	78,000	116,000	102,000	1.137	14.2
12F97	78,000	110,500	102,000	1.083	8.8
12F96	78,000	94,500	102,000	.926	7.0
12F94	78,000	85,200	102,000	.835	16.1
				Av. .995	Av. ±11.5
12F111	76,000	159,000	133,000	1.195	19.7
12F110	76,000	146,500	133,000	1.102	10.4
12F113	76,000	139,100	133,000	1.046	4.8
12F117	76,000	110,400	133,000	.830	16.8
12F112	76,000	108,400	133,000	.815	18.2
				Av. .998	Av. ±14.0
12F92	72,000	324,400	220,000	1.474	28.4
12F93	72,000	321,200	220,000	1.460	27.1
12F118	72,000	234,600	220,000	1.066	7.2
12F58	72,000	130,400	220,000	.592	48.4
				Av. 1.148	Av. ±27.8
12F39	70,000	388,400	280,000	1.387	32.2
12F38	70,000	331,900	280,000	1.185	13.0
12F43	70,000	273,100	280,000	.975	7.1
12F42	70,000	253,500	280,000	.905	13.7
12F41	70,000	221,800	280,000	.792	24.5
				Av. 1.049	Av. ±18.1

TABLE VI.- RESULTS OF 400° F TESTS AT ONE STRESS LEVEL - Concluded

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F109	68,000	502,900	356,000	1.413	27.9
12F48	68,000	403,200	356,000	1.133	2.5
12F49	68,000	343,800	356,000	.966	12.6
12F108	68,000	323,400	356,000	.908	17.8
				Av. 1.105	Av. ±15.2
12F55	66,000	691,800	460,000	1.504	42.2
12F54	66,000	558,500	460,000	1.214	14.9
12F56	66,000	422,900	460,000	.919	13.1
12F149	66,000	271,500	460,000	.590	44.2
				Av. 1.057	Av. ±28.6
12F157	64,000	940,900	590,000	1.595	97.6
12F156	64,000	544,600	590,000	.923	14.4
12F150	64,000	326,200	590,000	.553	31.5
12F155	64,000	293,800	594,000	.498	38.6
12F152	64,000	274,500	590,000	.465	42.4
				Av. .807	Av. ±44.9
12F160	62,000	10,106,800	(a b)		
12F161	62,000	8,117,200	(b)		
12F158	62,000	3,949,000	(b)		
12F159	62,000	376,300	(b)		
12F162	60,000	11,572,400	(a c)		
12F163	60,000	16,837,700	(a c)		

[a]Specimen did not fail.
[b]Stress corresponds to endurance limit.
[c]Stress below endurance limit.

TABLE VII.- RESULTS OF TWO-STEP TESTS AT 400° F BASED ON MEAN S-N CURVE

[From mean curve: N at 68,000 psi is 356,000 cycles, N at 70,000 psi is 280,000 cycles, N at 78,000 psi is 102,000 cycles, and N at 80,000 psi is 80,000 cycles]

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F164	68,000	80,000	0.250	0.493	0.743	2.7
12F165	68,000	80,000	.250	.563	.813	6.4
12F166	68,000	80,000	.250	.379	.629	17.7
12F168	68,000	80,000	.250	.621	.871	14.0
					Av. .764	Av. ±10.2
12F169	68,000	80,000	.500	.166	.666	6.1
12F170	68,000	80,000	.500	.069	.569	9.4
12F171	68,000	80,000	.500	.169	.669	6.5
12F172	68,000	80,000	.500	.108	.608	3.2
					Av. .628	Av. ±6.3
12F203	68,000	80,000	.569	0	.569	16.9
12F204	68,000	80,000	.604	0	.604	11.8
12F205	68,000	80,000	.750	.018	.768	12.1
12F206	68,000	80,000	.750	.049	.799	16.6
					Av. .685	Av. ±14.4
12F210	80,000	68,000	.250	.231	.481	4.3
12F211	80,000	68,000	.250	.154	.404	12.4
12F212	80,000	68,000	.250	.248	.498	8.0
12F215	80,000	68,000	.250	.212	.462	.2
					Av. .461	Av. ±6.2
12F216	80,000	68,000	.500	.128	.628	4.0
12F217	80,000	68,000	.500	.093	.593	1.8
12F219	80,000	68,000	.500	.094	.594	1.7
12F220	80,000	68,000	.500	.102	.602	.3
					Av. .604	Av. ±2.0
12F224	80,000	68,000	.648	0	.648	9.1
12F225	80,000	68,000	.656	0	.656	8.0
12F226	80,000	68,000	.684	0	.684	4.1
12F227	80,000	68,000	.750	.112	.862	20.9
					Av. .713	Av. ±10.5

TABLE VII.- RESULTS OF TWO-STEP TESTS AT 400° F BASED ON

MEAN S-N CURVE - Concluded

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum\frac{n}{N}$	Deviation from average, percent
12F228	70,000	78,000	0.250	0.436	0.686	14.2
12F229	70,000	78,000	.250	.585	.835	4.4
12F258	70,000	78,000	.250	.651	.901	12.6
12F259	70,000	78,000	.250	.528	.778	2.7
					Av. .800	Av. ±8.5
12F261	70,000	78,000	.500	.672	1.172	11.4
12F262	70,000	78,000	.500	.547	1.047	.5
12F264	70,000	78,000	.500	.296	.796	24.3
12F272	70,000	78,000	.500	.691	1.191	13.2
					Av. 1.052	Av. ±12.4
12F266	70,000	78,000	.750	.133	.883	18.4
12F267	70,000	78,000	.654	0	.654	12.3
12F268	70,000	78,000	.750	.039	.789	5.8
12F269	70,000	78,000	.659	0	.659	11.7
					Av. .746	Av. ±12.1
12F275	78,000	70,000	.250	.271	.521	5.5
12F276	78,000	70,000	.250	.176	.426	13.8
12F278	78,000	70,000	.250	.198	.448	9.3
12F279	78,000	70,000	.250	.332	.582	17.8
					Av. .494	Av. ±11.6
12F280	78,000	70,000	.500	.134	.634	2.3
12F281	78,000	70,000	.500	.158	.658	1.4
12F282	78,000	70,000	.500	.118	.618	4.8
12F284	78,000	70,000	.500	.185	.685	5.5
					Av. .649	Av. ±3.5
12F285	78,000	70,000	.750	.054	.804	4.8
12F286	78,000	70,000	.728	0	.728	5.1
12F288	78,000	70,000	.676	0	.676	11.9
12F289	78,000	70,000	.750	.110	.860	12.1
					Av. .767	Av. ±8.5

TABLE VIII.- RESULTS OF TWO-STEP TESTS AT 400° F BASED ON

MINIMUM S-N CURVE

[From minimum curve: N at 68,000 psi is 181,000 cycles, N at 70,000 psi is 154,000 cycles, N at 78,000 psi is 79,000 cycles, and N at 80,000 psi is 67,000 cycles]

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F164	68,000	80,000	0.492	0.588	1.080	2.4
12F165	68,000	80,000	.492	.672	1.164	5.2
12F166	68,000	80,000	.492	.452	.944	14.6
12F168	68,000	80,000	.492	.742	1.234	11.2
					Av. 1.106	Av. ±8.4
12F169	68,000	80,000	.983	.199	1.182	4.0
12F170	68,000	80,000	.983	.082	1.065	6.2
12F171	68,000	80,000	.983	.201	1.184	4.2
12F172	68,000	80,000	.983	.128	1.111	2.2
					Av. 1.136	Av. ±4.2
12F203	68,000	80,000	1.119	0	1.119	16.1
12F204	68,000	80,000	1.189	0	1.189	10.9
12F205	68,000	80,000	1.475	.021	1.496	12.1
12F206	68,000	80,000	1.475	.058	1.533	14.9
					Av. 1.334	Av. ±13.5
12F210	80,000	68,000	.299	.455	.754	5.5
12F211	80,000	68,000	.299	.304	.603	15.7
12F212	80,000	68,000	.299	.487	.786	9.9
12F215	80,000	68,000	.299	.417	.716	.1
					Av. .715	Av. ±7.8
12F216	80,000	68,000	.597	.251	.848	5.7
12F217	80,000	68,000	.597	.183	.780	2.7
12F219	80,000	68,000	.597	.186	.783	2.4
12F220	80,000	68,000	.597	.200	.797	.6
					Av. .802	Av. ±2.9
12F224	80,000	68,000	.773	0	.783	10.5
12F225	80,000	68,000	.784	0	.784	10.4
12F226	80,000	68,000	.816	0	.816	6.7
12F227	80,000	68,000	.896	.219	1.115	27.4
					Av. .875	Av. ±13.8

TABLE VIII.- RESULTS OF TWO-STEP TESTS AT 400° F BASED ON

MINIMUM S-N CURVE - Concluded

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F228	70,000	78,000	0.455	0.563	1.018	12.7
12F229	70,000	78,000	.455	.756	1.211	3.9
12F258	70,000	78,000	.455	.841	1.296	11.1
12F259	70,000	78,000	.455	.682	1.137	2.5
					Av. 1.166	Av. ±7.6
12F261	70,000	78,000	.909	.867	1.776	9.6
12F262	70,000	78,000	.909	.706	1.615	.4
12F264	70,000	78,000	.909	.382	1.291	20.4
12F272	70,000	78,000	.909	.892	1.801	11.1
					Av. 1.621	Av. ±10.4
12F266	70,000	78,000	1.364	.172	1.536	15.1
12F267	70,000	78,000	1.190	0	1.190	10.9
12F268	70,000	78,000	1.364	.051	1.415	6.0
12F269	70,000	78,000	1.197	0	1.197	10.3
					Av. 1.335	Av. ±10.6
12F275	78,000	70,000	.323	.492	.815	6.3
12F276	78,000	70,000	.323	.319	.642	16.3
12F278	78,000	70,000	.323	.360	.683	11.0
12F279	78,000	70,000	.323	.603	.926	20.7
					Av. .767	Av. ±13.6
12F280	78,000	70,000	.646	.243	.889	2.9
12F281	78,000	70,000	.646	.288	.934	2.0
12F282	78,000	70,000	.646	.214	.860	6.1
12F284	78,000	70,000	.646	.336	.982	7.2
					Av. .916	Av. ±4.6
12F285	78,000	70,000	.968	.097	1.065	5.2
12F286	78,000	70,000	.941	0	.941	7.0
12F288	78,000	70,000	.873	0	.873	13.7
12F289	78,000	70,000	.968	.200	1.168	15.4
					Av. 1.012	Av. ±10.3

TABLE IX.- RESULTS OF THREE-STEP TESTS AT 400° F BASED ON MEAN S-N CURVE

[From mean curve: N at 68,000 psi is 356,000 cycles, N at 74,000 psi is 170,000 cycles, and N at 80,000 psi is 80,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F290	68,000	74,000	80,000	0.300	0.300	0.911	1.511	18.0
12F291	68,000	74,000	80,000	.300	.300	.649	1.249	2.5
12F292	68,000	74,000	80,000	.300	.300	.393	.993	22.5
12F293	68,000	74,000	80,000	.300	.300	.771	1.371	7.0
							Av. 1.281	Av. ±12.5
12F295	80,000	74,000	68,000	.300	.266	0	.566	9.1
12F297	80,000	74,000	68,000	.300	.300	.024	.624	.2
12F298	80,000	74,000	68,000	.300	.300	.036	.636	2.1
12F299	80,000	74,000	68,000	.300	.300	.064	.664	6.6
							Av. .623	Av. ±4.5

TABLE X.- RESULTS OF THREE-STEP TESTS AT 400° F BASED ON

MINIMUM S-N CURVE

[From minimum curve: N at 68,000 psi is 181,000 cycles, N at 74,000 psi is 111,000 cycles, and N at 80,000 psi is 67,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	Cumulative cycle ratio, $\sum\frac{n}{N}$	Deviation from average, percent
12F290	68,000	74,000	80,000	0.590	0.459	1.088	2.137	14.8
12F291	68,000	74,000	80,000	.590	.459	.775	1.824	2.0
12F292	68,000	74,000	80,000	.590	.459	.469	1.518	18.5
12F293	68,000	74,000	80,000	.590	.459	.921	1.970	5.8
							Av. 1.862	Av. ±10.3
12F295	80,000	74,000	68,000	.358	.407	0	.765	11.6
12F297	80,000	74,000	68,000	.358	.459	.046	.863	.2
12F298	80,000	74,000	68,000	.358	.459	.071	.888	2.7
12F299	80,000	74,000	68,000	.358	.459	.126	.943	9.0
							Av. .865	Av. ±5.9

TABLE XI.- RESULTS OF FIVE-STEP TESTS AT 400° F BASED ON MEAN S-N CURVE

[From mean curve: N at 68,000 psi is 356,000 cycles, N at 70,000 psi is 280,000 cyles, N at 72,000 psi is 220,000 cycles, N at 74,000 psi is 170,000 cycles, and N at 76,000 psi is 133,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	R_4, $\frac{n_4}{N_4}$	R_5, $\frac{n_5}{N_5}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F300	68,000	70,000	72,000	74,000	76,000	0.200	0.200	0.200	0.200	0.559	1.359	11.7
12F301	68,000	70,000	72,000	74,000	76,000	.200	.200	.200	.200	.738	1.538	.6
12F302	68,000	70,000	72,000	74,000	76,000	.200	.200	.200	.200	1.244	2.044	32.8
12F304	68,000	70,000	72,000	74,000	76,000	.200	.200	.200	.200	.414	1.214	21.1
											Av. 1.539	Av. ±16.6
12F305	76,000	74,000	72,000	70,000	68,000	.200	.200	.172	0	0	.572	19.3
12F307	76,000	74,000	72,000	70,000	68,000	.200	.200	.200	.165	0	.765	7.9
12F308	76,000	74,000	72,000	70,000	68,000	.200	.200	.200	.177	0	.777	9.6
12F309	76,000	74,000	72,000	70,000	68,000	.200	.200	.200	.123	0	.723	2.0
											Av. .709	Av. ±9.7
12F310	68,000	76,000	68,000	76,000	68,000	.200	.200	.200	.162	0	.762	17.4
12F311	68,000	76,000	68,000	76,000	68,000	.200	.200	.078	0	0	.478	26.3
12F312	68,000	76,000	68,000	76,000	68,000	.200	.200	.200	.001	0	.601	7.4
12F313	68,000	76,000	68,000	76,000	68,000	.200	.200	.200	.153	0	.753	16.0
											Av. .649	Av. ±16.8

TABLE XII.- RESULTS OF FIVE-STEP TESTS AT 400° F BASED ON MINIMUM S-N CURVE

[From minimum curve: N at 68,000 psi is 181,000 cycles, N at 70,000 psi is 154,000 cycles, N at 72,000 psi is 131,000 cycles, N at 74,000 psi is 111,000 cycles, and N at 76,000 psi is 93,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	R_4, $\frac{n_4}{N_4}$	R_5, $\frac{n_5}{N_5}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F300	68,000	70,000	72,000	74,000	76,000	0.393	0.364	0.336	0.306	0.800	2.199	10.5
12F301	68,000	70,000	72,000	74,000	76,000	.393	.364	.336	.306	1.056	2.455	0
12F302	68,000	70,000	72,000	74,000	76,000	.393	.364	.336	.306	1.780	3.179	29.4
12F304	68,000	70,000	72,000	74,000	76,000	.393	.364	.336	.306	.592	1.991	18.9
											Av. 2.456	Av.±14.7
12F305	76,000	74,000	72,000	70,000	68,000	.286	.306	.289	0	0	.881	21.8
12F307	76,000	74,000	72,000	70,000	68,000	.286	.306	.336	.299	0	1.227	8.9
12F308	76,000	74,000	72,000	70,000	68,000	.286	.306	.336	.322	0	1.250	10.9
12F309	76,000	74,000	72,000	70,000	68,000	.286	.306	.336	.223	0	1.151	2.1
											Av. 1.127	Av.±10.9
12F310	68,000	76,000	68,000	76,000	68,000	.393	.286	.393	.231	0	1.303	15.5
12F311	68,000	76,000	68,000	76,000	68,000	.393	.286	.153	0	0	.832	26.2
12F312	68,000	76,000	68,000	76,000	68,000	.393	.286	.393	.014	0	1.086	3.7
12F313	68,000	76,000	68,000	76,000	68,000	.393	.286	.393	.219	0	1.291	14.5
											Av. 1.128	Av.±15.0

TABLE XIII.- COMPARISON OF 400° F TEST RESULTS WITH RESULTS COMPUTED BY HENRY'S THEORY (REF. 34)

S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	$\frac{n_1}{N_1}$	$\frac{n_2}{N_2}$	$\frac{n_3}{N_3}$	$\frac{n_4}{N_4}$	Cumulative cycle ratio: Test average (a)	Cumulative cycle ratio: Henry's theory
Two-step tests										
68,000	80,000				0.492				1.106	1.216
68,000	80,000				.983				1.136	1.025
68,000	80,000				1.475				1.334	(b)
80,000	68,000				.299				.715	.775
80,000	68,000				.597				.802	.807
80,000	68,000				.896				.875	.940
70,000	78,000				.455				1.166	1.139
70,000	78,000				.909				1.621	1.061
70,000	78,000				1.364				1.335	(b)
78,000	70,000				.323				.767	.864
78,000	70,000				.646				.916	.880
78,000	70,000				.968				1.012	.986
Three-step tests										
68,000	74,000	80,000			0.590	0.459			1.862	1.184
80,000	74,000	68,000			.358	.459			.865	.877
Five-step tests										
68,000	70,000	72,000	74,000	76,000	0.393	0.364	0.336	0.306	2.456	1.105
76,000	74,000	72,000	70,000	68,000	.286	.306	.336	.364	1.127	.937
68,000	76,000	68,000	76,000	68,000	.393	.286	.393	.286	1.128	.986

[a]From results based on minimum S-N curve.

[b]Theoretical analysis not applicable since cycle ratio at initial stress exceeds unity.

TABLE XIV.- RESULTS OF 800° F TESTS AT ONE STRESS LEVEL

[N obtained from mean S-N curve]

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F342	82,000	41,100	40,000	1.028	18.5
12F363	82,000	49,400	40,000	1.235	2.9
12F344	82,000	53,100	40,000	1.328	5.2
12F345	82,000	58,200	40,000	1.455	15.3
				Av. 1.262	Av. ±10.5
12F347	80,000	40,900	65,000	.629	33.4
12F346	80,000	43,200	65,000	.665	29.6
12F365	80,000	45,200	65,000	.695	26.4
12F364	80,000	47,200	65,000	.726	23.1
12F325	80,000	62,800	65,000	.966	2.3
12F330	80,000	79,800	65,000	1.228	30.0
12F327	80,000	110,200	65,000	1.700	80.0
				Av. .944	Av. ±32.1
12F348	78,000	65,800	110,000	.598	42.1
12F431	78,000	75,000	110,000	.682	34.0
12F435	78,000	102,100	110,000	.928	10.2
12F323	78,000	103,600	110,000	.942	8.8
12F432	78,000	111,200	110,000	1.011	2.1
12F334	78,000	127,700	110,000	1.161	12.3
12F434	78,000	131,800	110,000	1.198	16.0
12F335	78,000	192,200	110,000	1.747	69.1
				Av. 1.033	Av. ±24.3
12F350	76,000	93,800	184,000	.510	50.6
12F372	76,000	132,600	184,000	.721	30.0
12F371	76,000	222,800	184,000	1.211	17.2
12F322	76,000	226,900	184,000	1.233	19.4
12F352	76,000	274,600	184,000	1.492	44.4
				Av. 1.033	Av. ±32.3
12F353	74,000	360,800	308,000	1.171	8.4
12F354	74,000	377,800	308,000	1.227	4.0
12F355	74,000	417,300	308,000	1.355	6.0
12F321	74,000	418,100	308,000	1.357	6.2
				Av. 1.278	Av. ±6.2

TABLE XIV.- RESULTS OF 800° F TESTS AT ONE STRESS LEVEL - Continued

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F367	72,000	181,100	518,000	0.350	71.1
12F433	72,000	235,000	518,000	.454	62.5
12F320	72,000	493,000	518,000	.952	21.4
12F368	72,000	571,400	518,000	1.103	8.9
12F436	72,000	732,800	518,000	1.415	16.8
12F369	72,000	867,100	518,000	1.674	38.2
12F366	72,000	1,118,500	518,000	2.159	78.3
				Av. 1.211	Av. ±42.4
12F356	70,000	759,300	860,000	.883	33.3
12F438	70,000	803,500	860,000	.934	29.4
12F340	70,000	1,043,000	860,000	1.212	8.4
12F437	70,000	1,141,700	860,000	1.327	.3
12F440	70,000	1,193,800	860,000	1.388	4.9
12F341	70,000	1,223,000	860,000	1.422	7.5
12F319	70,000	1,328,300	860,000	1.544	16.7
12F339	70,000	1,617,500	860,000	1.880	42.1
				Av. 1.323	Av. ±17.8
12F381	68,000	518,100	1,500,000	.345	60.1
12F384	68,000	654,300	1,500,000	.436	49.5
12F383	68,000	742,100	1,500,000	.495	42.6
12F382	68,000	820,300	1,500,000	.547	36.6
12F358	68,000	1,113,300	1,500,000	.742	14.1
12F357	68,000	1,671,000	1,500,000	1.114	29.0
12F318	68,000	2,293,300	1,500,000	1.529	77.1
12F337	68,000	2,545,800	1,500,000	1.697	96.6
				Av. .863	Av. ±50.7
12F317	66,000	3,374,800	3,120,000	1.082	19.9
12F332	66,000	3,994,000	3,120,000	1.280	5.2
12F326	66,000	4,303,700	3,120,000	1.379	2.1
12F328	66,000	5,178,500	3,120,000	1.660	30.0
				Av. 1.350	Av. ±14.3

TABLE XIV.- RESULTS OF 800° F TESTS AT ONE STRESS LEVEL - Concluded

Specimen number	Stress, psi	Cycles to failure, n	Mean life, N	Cycle ratio, $\frac{n}{N}$	Deviation from average, percent
12F362	65,000	2,807,600	5,150,000	0.545	58.4
12F360	65,000	4,287,700	5,150,000	.833	36.4
12F359	65,000	4,748,700	5,150,000	.922	29.6
12F370	65,000	8,677,600	5,150,000	1.685	28.6
12F361	65,000	13,223,500	5,150,000	2.567	96.0
				Av. 1.310	Av. ±49.8

TABLE XV.- RESULTS OF TWO-STEP TESTS AT 800° F

[From mean curve: N at 74,000 psi is 308,000 cycles and N at 78,000 psi is 110,000 cycles]

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum\frac{n}{N}$	Deviation from average, percent
12F478	74,000	78,000	0.250	0.709	0.959	21.3
12F446	74,000	78,000	.250	.837	1.087	10.8
12F442	74,000	78,000	.250	.865	1.115	8.5
12F473	74,000	78,000	.250	1.211	1.461	19.9
12F444	74,000	78,000	.250	1.225	1.475	21.0
					Av. 1.219	Av. ±16.3
12F451	74,000	78,000	.500	.426	.926	21.1
12F482	74,000	78,000	.500	.468	.968	17.5
12F477	74,000	78,000	.500	.567	1.067	9.1
12F447	74,000	78,000	.500	.930	1.430	21.8
12F483	74,000	78,000	.500	.981	1.481	26.1
					Av. 1.174	Av. ±19.1
12F454	74,000	78,000	.581	0	.581	43.4
12F481	74,000	78,000	.750	.250	1.000	2.6
12F452	74,000	78,000	.750	.327	1.077	4.9
12F456	74,000	78,000	.750	.699	1.449	41.1
					Av. 1.027	Av. ±23.0
12F460	78,000	74,000	.250	.141	.391	22.9
12F459	78,000	74,000	.250	.224	.474	6.5
12F457	78,000	74,000	.250	.273	.523	3.2
12F461	78,000	74,000	.250	.390	.640	26.2
					Av. .507	Av. ±14.7
12F467	78,000	74,000	.500	.006	.506	18.4
12F463	78,000	74,000	.500	.069	.569	8.2
12F466	78,000	74,000	.500	.100	.600	3.2
12F465	78,000	74,000	.500	.305	.805	29.8
					Av. .620	Av. ±14.9
12F470	78,000	74,000	.623	0	.623	12.1
12F472	78,000	74,000	.626	0	.626	11.7
12F469	78,000	74,000	.719	0	.719	1.4
12F485	78,000	74,000	.750	.027	.777	9.6
12F468	78,000	74,000	.750	.049	.799	12.7
					Av. .709	Av. ±11.9

TABLE XV.- RESULTS OF TWO-STEP TESTS AT 800° F - Concluded

Specimen number	S_1, psi	S_2, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviative from average, percent
12F491	80,000	72,000	0.250	0.085	0.335	41.8
12F487	80,000	72,000	.250	.309	.559	2.9
12F488	80,000	72,000	.250	.343	.593	3.0
12F492	80,000	72,000	.250	.566	.816	41.7
					Av. .576	Av. ±22.4
12F496	80,000	72,000	.454	0	.454	10.8
12F494	80,000	72,000	.500	.001	.501	1.6
12F497	80,000	72,000	.500	.029	.529	3.9
12F495	80,000	72,000	.500	.053	.553	8.6
					Av. .509	Av. ±6.2
12F502	80,000	72,000	.514	0	.514	20.1
12F498	80,000	72,000	.586	0	.586	8.9
12F503	80,000	72,000	.628	0	.628	2.3
12F500	80,000	72,000	.692	0	.692	7.6
12F499	80,000	72,000	.750	.044	.794	23.5
					Av. .643	Av. ±12.5
12F507	72,000	80,000	.250	.597	.847	24.3
12F506	72,000	80,000	.250	.905	1.155	3.2
12F508	72,000	80,000	.250	.958	1.208	8.0
12F504	72,000	80,000	.250	1.015	1.265	13.0
					Av. 1.119	Av. ±12.1
12F510	72,000	80,000	.500	.614	1.114	27.1
12F509	72,000	80,000	.500	.646	1.146	25.0
12F511	72,000	80,000	.500	1.209	1.709	11.8
12F512	72,000	80,000	.500	1.306	1.806	18.1
12F513	72,000	80,000	.500	1.371	1.871	22.4
					Av. 1.529	Av. ±20.9
12F514	72,000	80,000	.750	.662	1.412	19.1
12F517	72,000	80,000	.750	.942	1.692	3.0
12F515	72,000	80,000	.750	1.049	1.799	3.1
12F516	72,000	80,000	.750	1.326	2.076	19.0
					Av. 1.745	Av. ±11.1

TABLE XVI.- RESULTS OF THREE-STEP TESTS AT 800° F

[From mean curve: N at 72,000 psi is 518,000 cycles, N at 76,000 psi is 184,000 cycles, and N at 80,000 psi is 65,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F522	72,000	76,000	80,000	0.300	0.209	0	0.509	12.8
12F528	72,000	76,000	80,000	.300	.257	0	.557	4.6
12F530	72,000	76,000	80,000	.300	.271	0	.571	2.2
12F526	72,000	76,000	80,000	.300	.300	.011	.611	4.6
12F525	72,000	76,000	80,000	.300	.300	.074	.674	15.4
							Av. .584	Av. ±7.9
12F532	80,000	76,000	72,000	.300	.078	0	.378	16.0
12F533	80,000	76,000	72,000	.300	.091	0	.391	13.1
12F531	80,000	76,000	72,000	.300	.110	0	.410	8.9
12F537	80,000	76,000	72,000	.300	.179	0	.479	6.4
12F535	80,000	76,000	72,000	.300	.208	0	.508	12.9
12F534	80,000	76,000	72,000	.300	.234	0	.534	18.7
							Av. .450	Av. ±12.7

TABLE XVII.- RESULTS OF FIVE-STEP TESTS AT 800° F

[From mean curve: N at 72,000 psi is 518,000 cycles, N at 74,000 psi is 308,000 cycles N at 76,000 psi is 184,000 cycles, N at 78,000 cycles is 110,000 cycles, and N at 80,000 psi is 65,000 cycles]

Specimen number	S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	R_1, $\frac{n_1}{N_1}$	R_2, $\frac{n_2}{N_2}$	R_3, $\frac{n_3}{N_3}$	R_4, $\frac{n_4}{N_4}$	R_5, $\frac{n_5}{N_5}$	Cumulative cycle ratio, $\sum \frac{n}{N}$	Deviation from average, percent
12F539	72,000	74,000	76,000	78,000	80,000	0.200	0.200	0.184	0	0	0.584	33.9
12F543	72,000	74,000	76,000	78,000	80,000	.200	.200	.200	.172	0	.772	12.7
12F538	72,000	74,000	76,000	78,000	80,000	.200	.200	.200	.200	.109	.909	2.8
12F540	72,000	74,000	76,000	78,000	80,000	.200	.200	.200	.200	.471	1.271	43.7
											Av. .884	Av. ±23.3
12F548	80,000	78,000	76,000	74,000	72,000	.200	.200	.013	0	0	.413	10.0
12F546	80,000	78,000	76,000	74,000	72,000	.200	.200	.036	0	0	.436	5.0
12F549	80,000	78,000	76,000	74,000	72,000	.200	.200	.043	0	0	.443	3.5
12F547	80,000	78,000	76,000	74,000	72,000	.200	.200	.152	0	0	.542	18.1
											Av. .459	Av. ±9.2
12F556	72,000	80,000	72,000	80,000	72,000	.200	.069	0	0	0	.269	29.0
12F552	72,000	80,000	72,000	80,000	72,000	.200	.192	0	0	0	.392	3.4
12F550	72,000	80,000	72,000	80,000	72,000	.200	.200	.033	0	0	.433	14.2
12F554	72,000	80,000	72,000	80,000	72,000	.200	.200	.022	0	0	.422	11.3
											Av. .379	Av. ±14.5

TABLE XVIII.- COMPARISON OF 800° F TEST RESULTS WITH RESULTS COMPUTED BY HENRY'S THEORY (REF. 34)

S_1, psi	S_2, psi	S_3, psi	S_4, psi	S_5, psi	$\frac{n_1}{N_1}$	$\frac{n_2}{N_2}$	$\frac{n_3}{N_3}$	$\frac{n_4}{N_5}$	Cumulative cycle ratio: Test average	Cumulative cycle ratio: Henry's theory
Two-step tests										
72,000	80,000				0.250				1.119	1.097
72,000	80,000				.500				1.529	1.147
72,000	80,000				.750				1.745	1.129
80,000	72,000				.250				.576	.867
80,000	72,000				.500				.509	.853
80,000	72,000				.750				.643	.904
74,000	78,000				.250				1.219	1.052
74,000	78,000				.500				1.174	1.072
74,000	78,000				.750				1.027	1.058
78,000	74,000				.250				.507	.939
78,000	74,000				.500				.620	.929
78,000	74,000				.750				.709	.950
Three-step tests										
72,000	76,000	80,000			0.300	0.300			0.584	1.133
80,000	76,000	72,000			300	.300			.450	.872
Five-step tests										
72,000	74,000	76,000	78,000	80,000	0.200	0.200	0.200	0.200	0.884	1.090
80,000	78,000	76,000	74,000	72,000	.200	.200	.200	.200	.459	.866
72,000	80,000	72,000	80,000	72,000	.200	.200	.200	.200	.379	.979

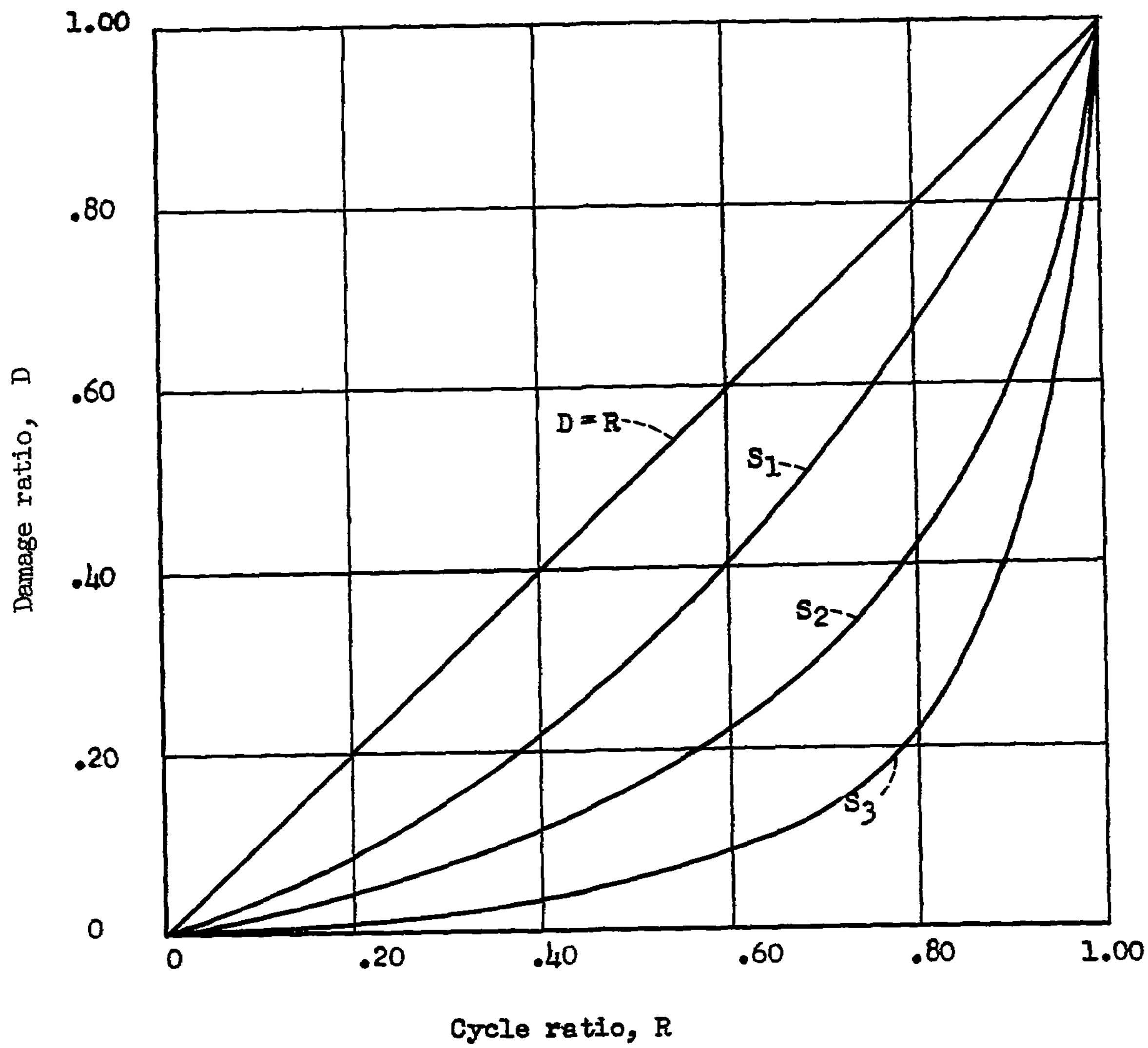


Figure 1.- Typical curves of damage ratio plotted against cycle ratio.

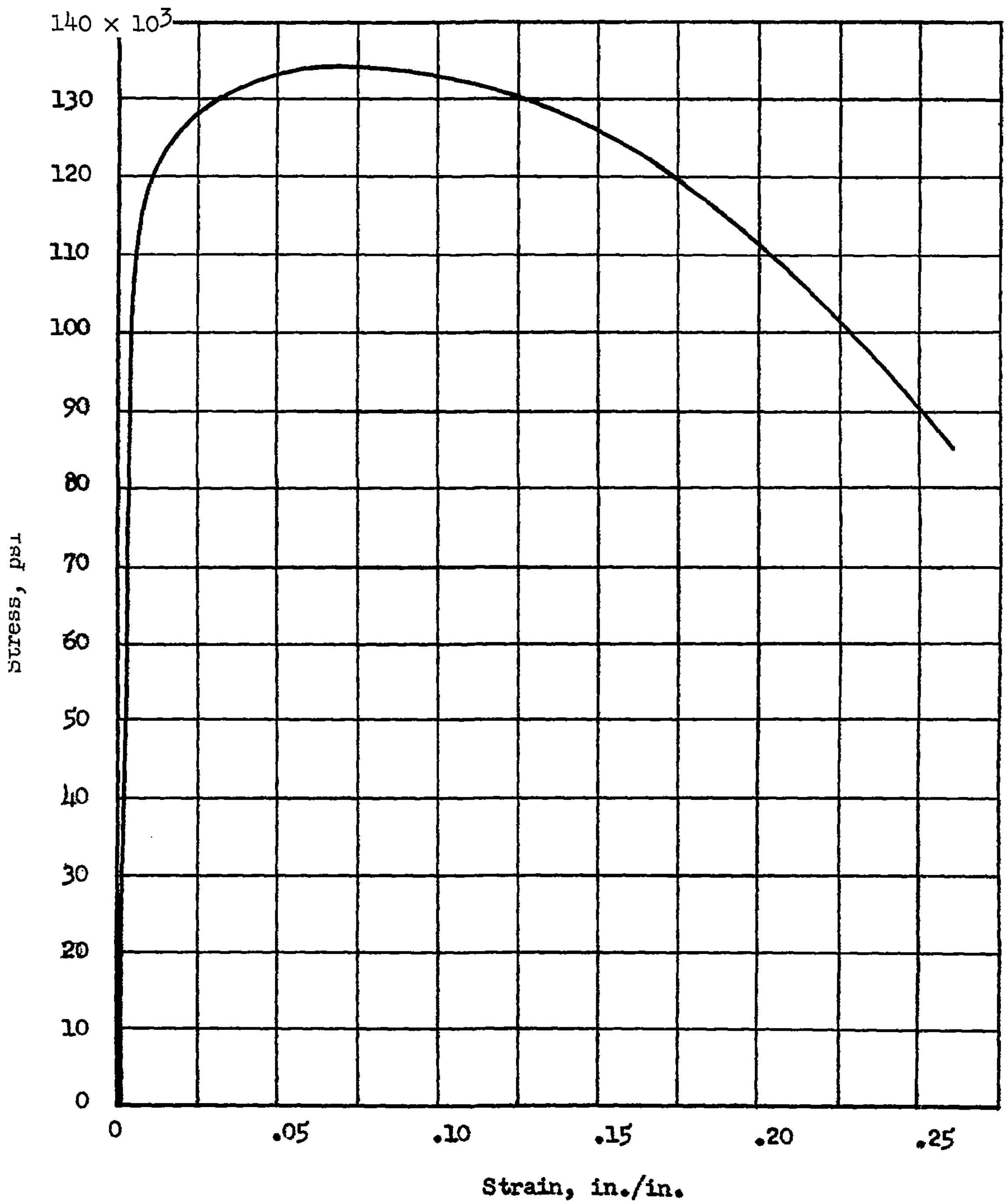


Figure 2.- Average tensile stress-strain curve for SAE 4130 stainless steel at room temperature.

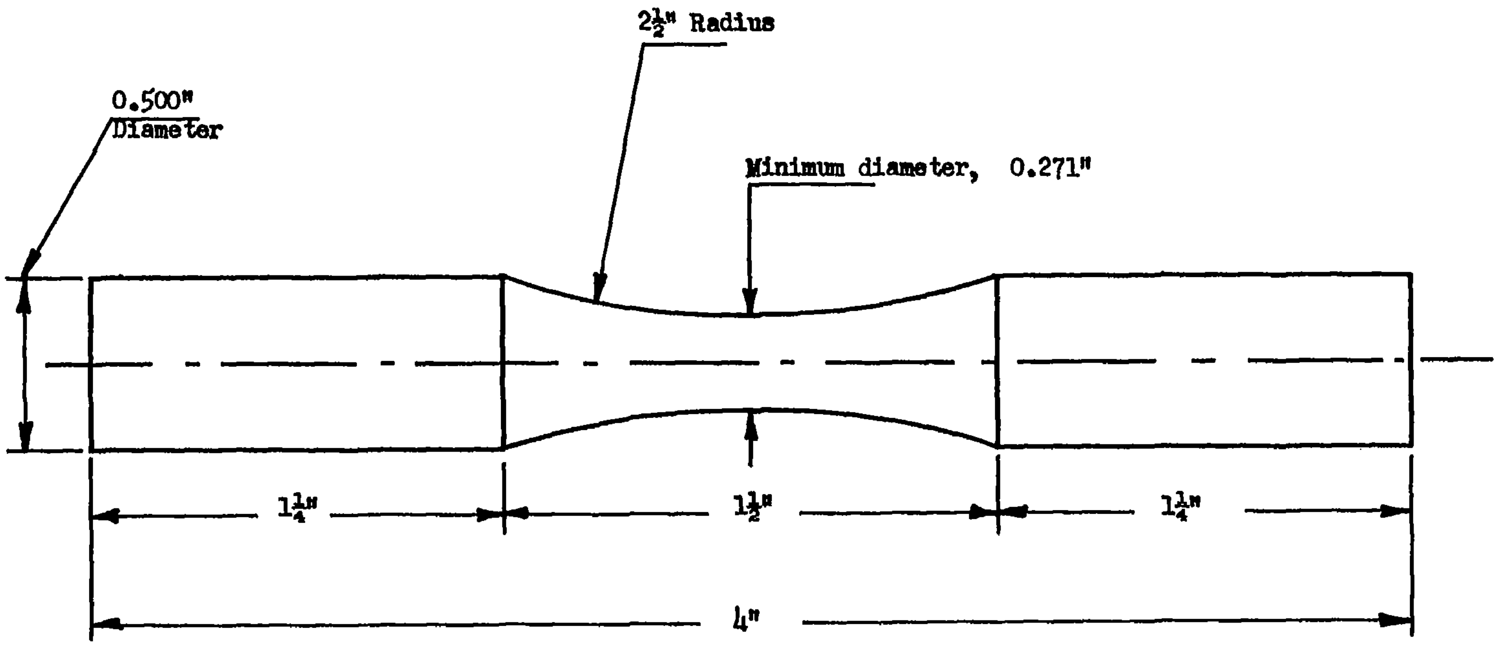


Figure 3.- Dimensions of $\frac{1}{2}$-inch-diameter rotating-beam fatigue specimen.

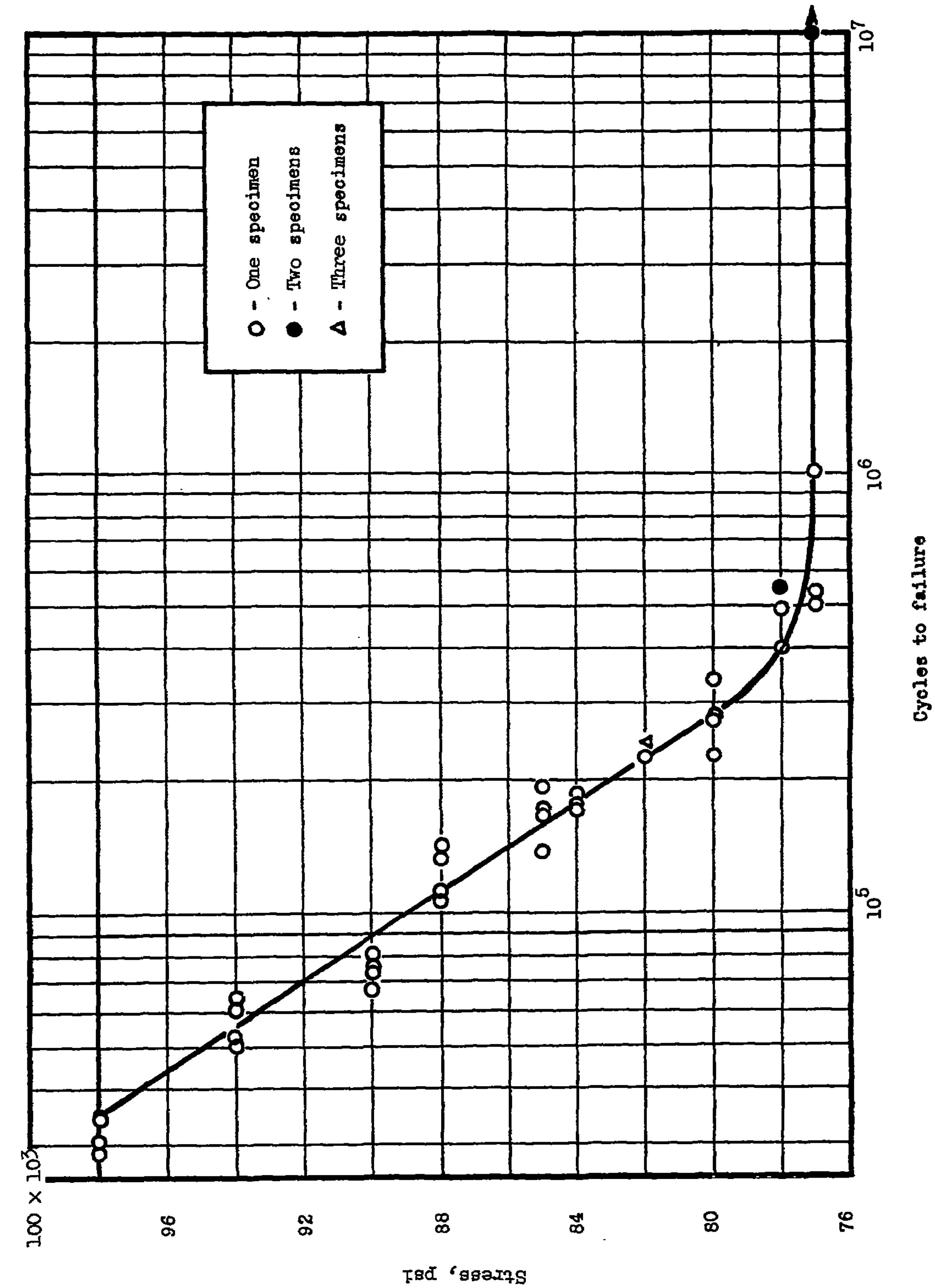


Figure 4.- S-N curve at room temperature.

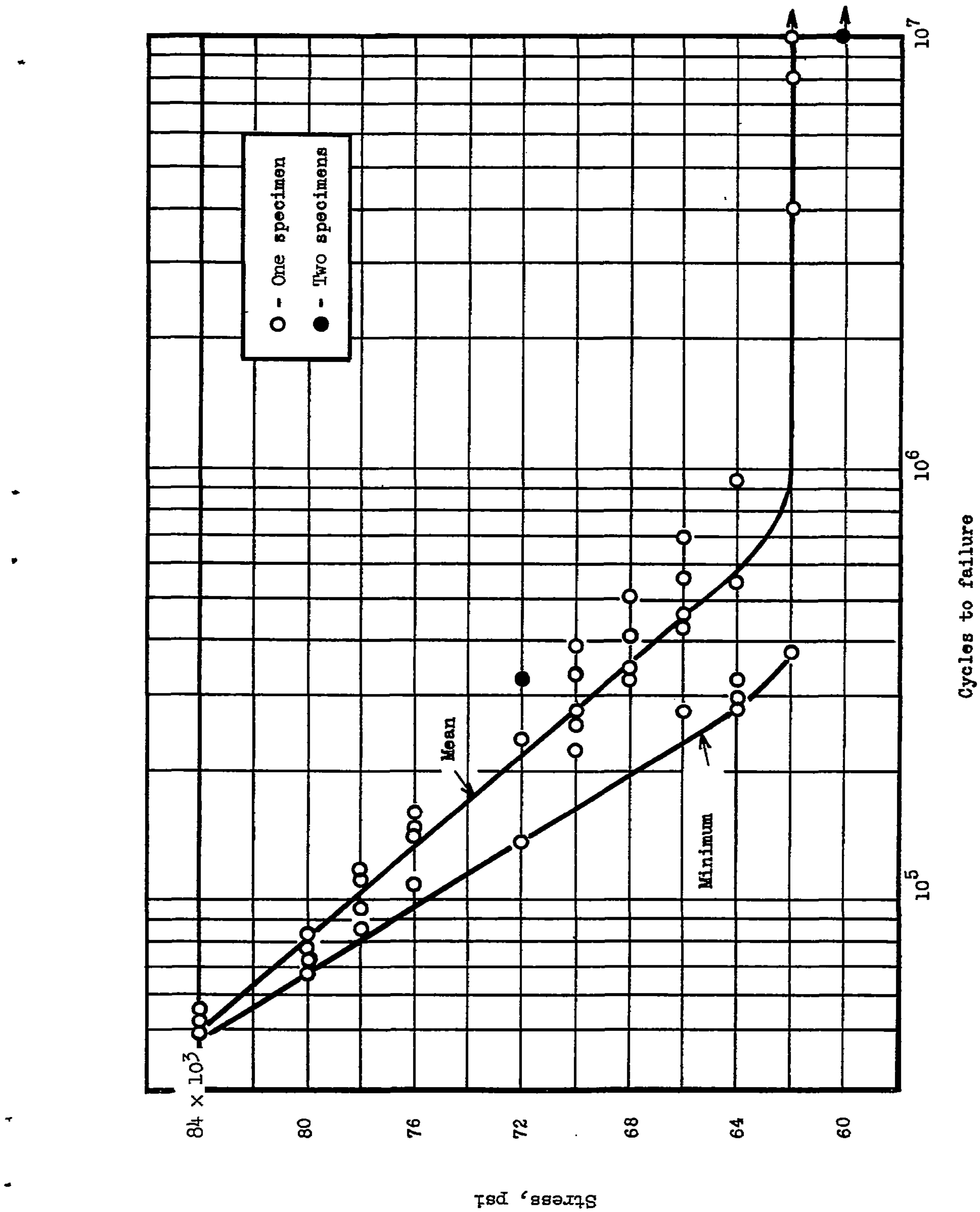
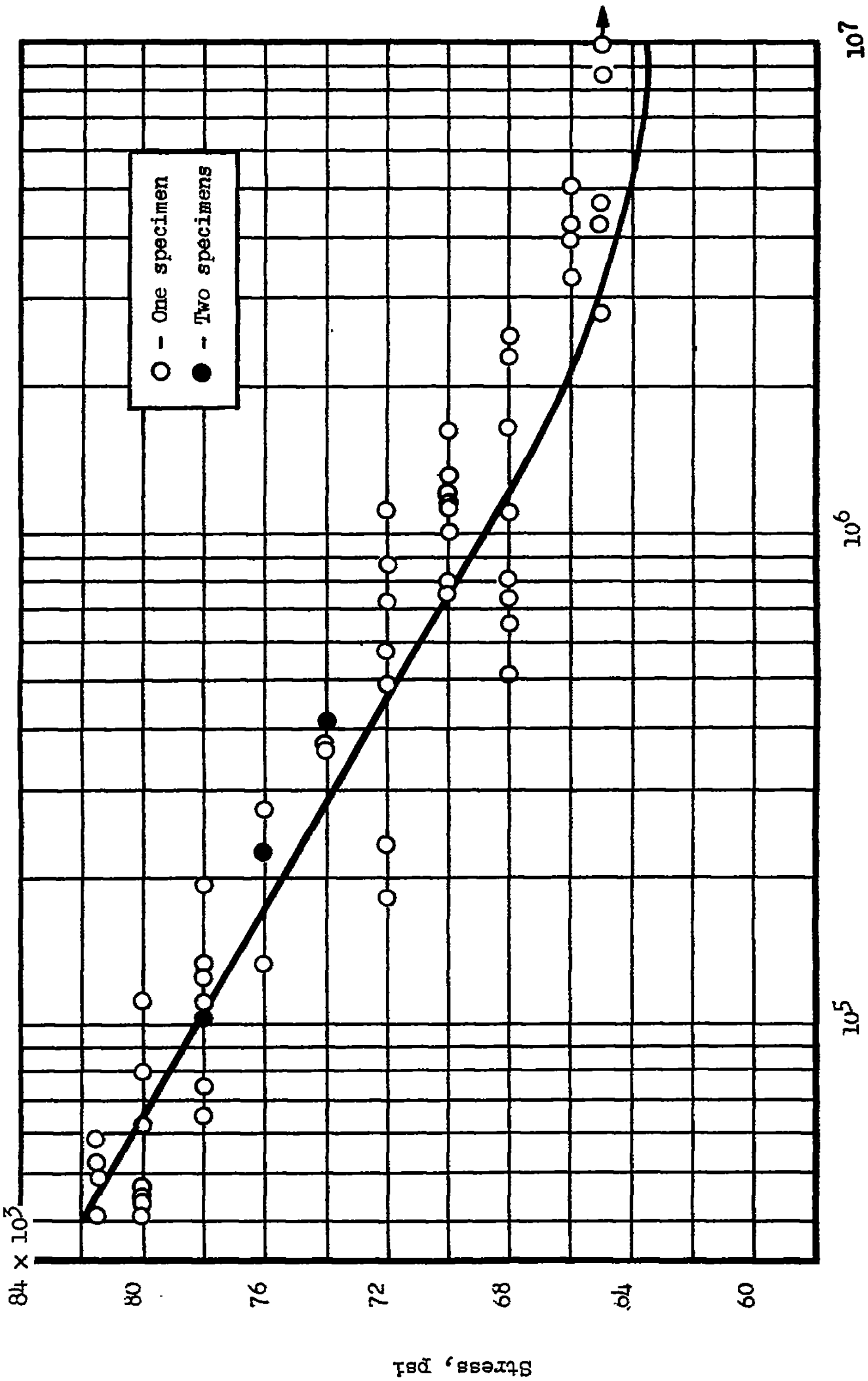


Figure 5.- S-N curve at 400° F.



Cycles to failure

Figure 6.- S-N curve at 800° F.

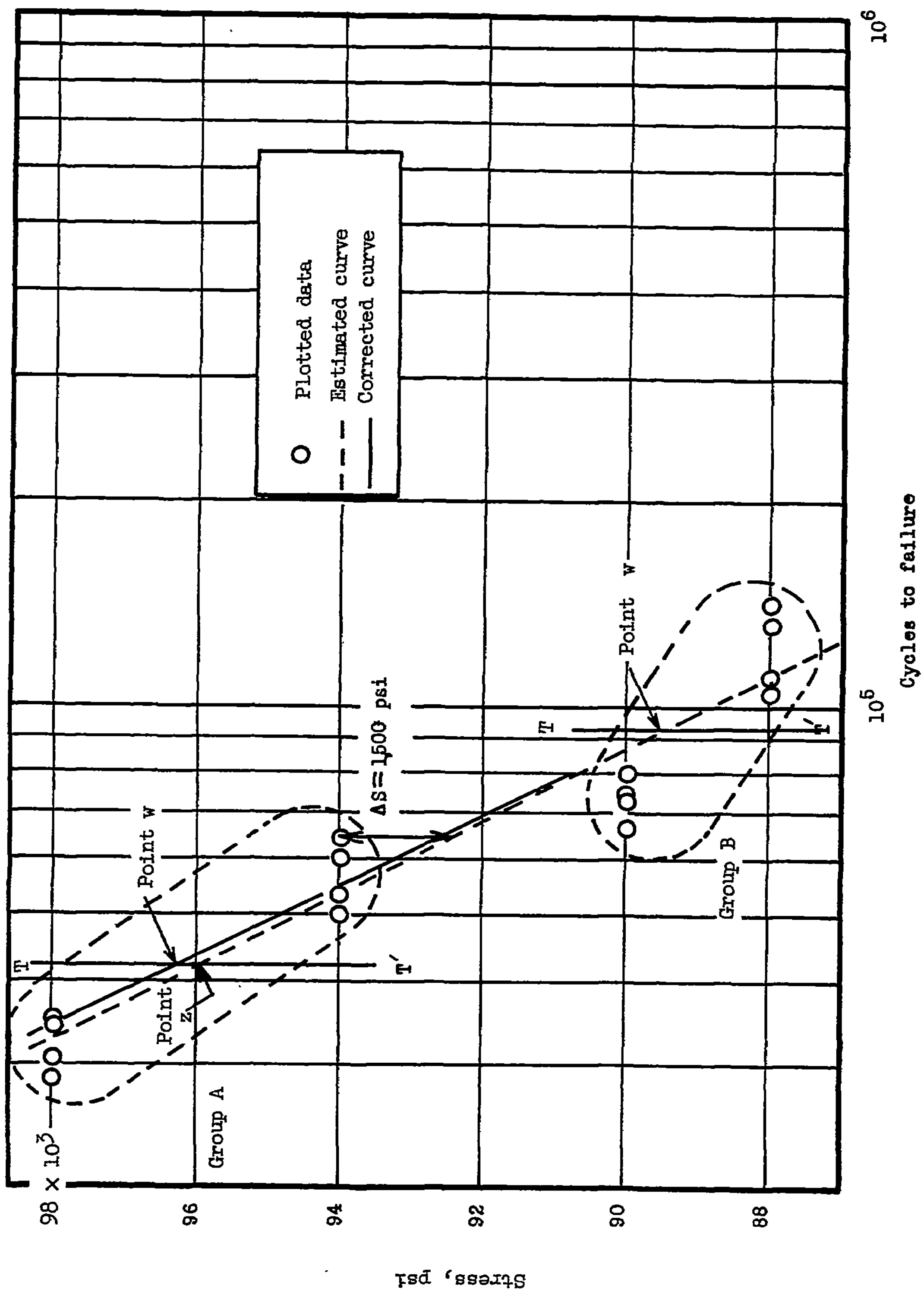


Figure 7.- Determination of mean curve.